CHEMICAL ENGINEERING, HEAT ENGINEERING AND ENERGY-SAVING

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THE COMPARISON OF THE MASS TRASFER EFFECIENCY IN DIFFERENT TYPES OF THE COMPLEX MODEL

Using the complex model for the counter-current and cross-current movement of liquid and vapor phases it is demonstrated that the mass-exchange efficiency increases when the phase equilibrium coefficient increases and other parameters of the construction and the working mode remain unchanged. An equation relating the mass-exchange efficiency for the mixtures with the phase equilibrium coefficients equal to one and much higher than one is derived. This equation can be used for evaluation of quantitative dependence of the mass-exchange efficiencies on the phase equilibrium coefficient.

Introduction. The frequently used definition of mass transfer efficiency, proposed by Murphree [1] assumes the equality of compositions of the vapor flowing on an ideal and real plates, and also the compositions of the liquid leaving these plates (efficiency on a vapor phase). In another version the Murphree concept is equal to the concentration of a vapor component in the liquid flowing on the specified plates, and also in the vapor leaving them (efficiency on liquid). In general vapor efficiency and liquid efficiency aren't equal. In the definition of mass transfer efficiency according to Hausen [2] the compositions of the vapor flowing on the ideal and real plates, and also the compositions of the liquid leaving them coincide. The efficiencies on vapor and liquid phases in the Hausen definition coincide. Besides, in the Murphree and Hausen concepts the complete mixture of liquid at a contact stage is considered and the features of direct-flow, counter-flow and cross movements of vapor and liquid phases aren't taken into consideration.

Making equal the compositions of cooperating phases at the inlet to the contact stage and the outlet from it obviously idealizes the real plate and underestimates indicators of work of the ideal plate. The stated features of the Murphree and Hausen concepts lead to essential errors in calculations of rectifying plates work parameters, in particular, mass transfer efficiency can exceed the real range of values.

To eliminate the stated shortcomings of the specified models there was offered a complex model in which the composition of inlet and outlet phases on the ideal and real plates differ [5–7]. In the ideal plate working more effectively the concentration of vapor component in the inlet phase should be less, and in the outlet phase there should be more corresponding values of flowing and leaving liquid.

According to the stated in a new model the concentration of a vapor component in the steam phase on the ideal and real plates is leveled in some space removed at distance h from the place of its input. The compositions of liquid on the ideal and real plates become equal in some space removed at distance h_1 from the place of input of liquid.

Thus, the complex model differs from the Murphree and Hausen concepts in the link conditions of the ideal and real plates. Other features of known models take place and in the complex model.

In works [3–5] there considered the features of mass transfer with reference to direct-flow, counterflow and cross movement of vapor and liquid phases. The received dependences of the difference of vapor component concentration in liquid before and after a plate are generalized [6] in

$$x_n - x_{n-1} = \frac{\left(x_{n-1} - \frac{y_{n-1}}{m}\right)E}{(1-h)\frac{L}{mV} + C - h_1 + h\frac{L}{mV}E + (1-h_1)E}, \quad (1)$$

where x_n, x_{n-1} – the concentration of the vapor component in liquid before and after the plate, g/mol; y_{n-1} – the concentration of the vapor component in a steam phase before the plate, g/mol; E – efficiency of mass transfer; L, V – discharge of liquid and steam phases respectively, mol/s; $m = y / x$ – the coefficient of distribution; C – the generalized value ($C = 1$ for direct flow; $C = 0$ for countercurrent; $C = 0.5$ for cross current).

At $h = 0$ and $h_1 = 1$ formula (1) coincides with the similar expression of the Murphree model in the efficiency analysis in a steam phase, at $h = 1$ and $h_1 = 0$ it coincides with the similar expression of the Murphree model in the efficiency analysis in liquid, at $h = 0$ and $h_1 = 0$ – the Hausen models. Thereof the complex model can be considered to be generalizing of the Murphree and Hausen

known concepts in which the dimensionless distances of h and h_1 accept limiting values 0 or 1.

In work [7] there is offered the dependence of distances h and h_1 on the distribution coefficient:

$$h = h_1 = \frac{1}{m+1}. \qquad (2)$$

The use of expression (2) in the specific case of the complex model makes it dynamic and allows to consider the change of the concentration on plates of the rectifying column.

Main part. According to the formula (2), the complex model depending on the distribution coefficient value is presented by two areas: in one of them $m > 1$, $h = h_1 < 0.5$ (Fig. 1, *a*); in the second – $m < 1$, $h = h_1 > 0.5$ (Fig. 1, *b*). The boundary case of these areas is the option at which the distribution coefficient is equal to $m = 1$, and distances of h and h_1 accept a half of full value, i.e. $h = h_1 = 0.5$. The physical sense of this option corresponds to the rectification of inseparably boiling, azeotropic mixtures. The efficiency analysis of mass transfer in this case isn't meaningful, but the cases of rectification of mixtures at which the distribution coefficient comes nearer to unity have practical value.

Through the solution of formulas (1) and (2) we can derive the ratios of difference of concentration and motive power at $m \neq 1$ (z) and at $m = 1$ (z_m):

$$z = \frac{x_n - x_{n-1}}{x_n - \frac{y_{n-1}}{m}} = \frac{E(m+1)}{\frac{L}{V} - 1 + C(m+1) + \frac{L}{mV}E - mE}; \qquad (3)$$

$$z_m = \frac{x_n - x_{n-1}}{x_n - y_{n-1}} = \frac{2E_m}{\frac{L}{V} - 1 + 2C + \frac{L}{V}E_m - E_m}. \qquad (4)$$

The mass transfer efficiency at rectification of binary mixes depends, on the one hand, on the design and regime data of a contact stage, and on the another hand – on the thermophysical properties of cooperating mixtures.

Viscosity and volatility have the most significant influence on the mass transfer efficiency in the known models [8]. The first for the majority of divided mixtures changes in rather small range and influences the mass transfer to a lesser extent ($E \approx \mu^{-0.9}$) than the second which is a synonym of the distribution coefficient. In the complex model according to (2) this influence is more significant. Therefore a certain interest represents the comparison of the mass transfer in the model which is most considering the distribution coefficient with the model in which this influence is insignificant or absent.

Other things being equal (plates design, operating mode, flow organization, liquid and vapor discharge) the mass transfer efficiency should be more for a mixture which has bigger distribution coefficient, and at achievement of identical technological indicators the mass transfer efficiency is supposed to be smaller for a mixture equal m, coming closer to unity.

For the comparative analysis of efficiencies of equalizing of the left and right parts of formulas (3) and (4) we have the following

$$E = \frac{\frac{L}{V} - 1 + C(m+1)}{\frac{\left(\frac{L}{V} - 1 + 2C\right)(m+1)}{2E_m} + (m-1)\left(\frac{L}{mV} + \frac{L}{2V} + \frac{1}{2}\right)}. \qquad (5)$$

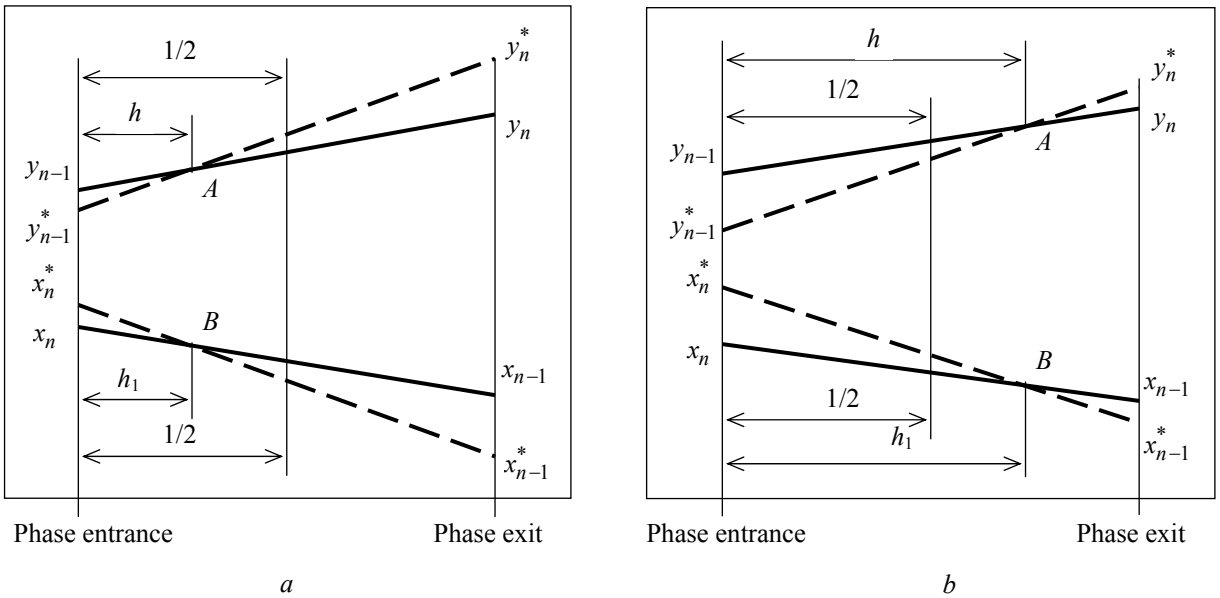

Fig. 1. The change of concentration on the real (continuous line) and ideal (dashed line) plates in various areas of the complex model: *a* – $m > 1$; $h = h_1 < 0.5$; *b* – $m < 1$; $h = h_1 > 0.5$

The graphic representation of dependence (5) is given on Fig. 2–4.

For the direct-flow movement of vapor and liquid phases (Fig. 2) there is noted the coincidence of efficiencies of E_g and E_{gm} at the distribution coefficient equal to unity that comes from the comparison of expressions (3) and (4) if the value $m = 1$ is used in the first.

As it appears from Fig. 2, *a*, at a direct flow and small values of the relation of L / V, there observed the comparable values of efficiencies of E_g и E_{gm} and only at $m < 0.5$ and $E_g > 0.4$ their considerable difference occurs. Besides at $E_{gm} > 0.5$ and $m < 0.5$ the values of E_g can be negative that is caused by restrictions of material balance when the quantity of the component evaporated from liquid, can't be completely absorbed by vapor. The relation of efficiencies depends on the distribution coefficient and on the efficiency value. For the values of efficiencies, less than 0.8, $E_g > E_{gm}$ at $m > 1$ and $E_g < E_{gm}$ at $m < 1$.

With the increase in the relation L / V (Fig. 2, *b*, *c*) the difference between the considered efficiencies increases and the range of real efficiencies values for $m < 0.5$ is narrowed. The data on the change in efficiencies considered additionally, but not given on Fig. 2, show that $E_g < E_{gm}$ at $L / V > 0.5$.

Thus, the assumption stated above about the increase in the mass transfer efficiency when m increases is confirmed graphically for direct flow for $L / V > 0.5$.

For countercurrent the mass transfer efficiency Eg is equal to zero at $L / V = 1$ and any m and E_g values (Fig. 3, *b*) that follows from a formula (5) at $C = 0$. In other cases ($L / V \neq 1$) to achieve the same technological indicators E_g can be less than E_{gm} that testifies the increase of the mass transfer efficiency at the increase in the distribution coefficient in the studied range of the relation L / V, that also confirms the assumption specified above that $E_g > E_{gm}$ at $m > 1$.

Thus for countercurrent there are also observed negative efficiencies for small m (Fig. 3, *c*), but, unlike direct flow, only for narrower range of the relations of liquid and vapor discharge ($L / V > 1$).

And this distinction is more significant in comparison with similar conditions for direct flow.

At $m \geq 1$ (Fig. 4, *b*, *c*) the opposite ratio of the efficiencies is noted that confirms higher mass transfer efficiency at the increase of the distribution coefficient.

There can also be negative efficiencies at $m < 1$ (Fig. 4), caused by the restrictions of material balance specified above.

The carried-out analysis shows that it is possible to conduct researches with certain design and regime features on the modeling mixture, for example the diluted solution of acetic acid, which distribution coefficient is a little more than unity, and recalculation on formula (5) the received efficiency at the same contact stage for other divided mixes.

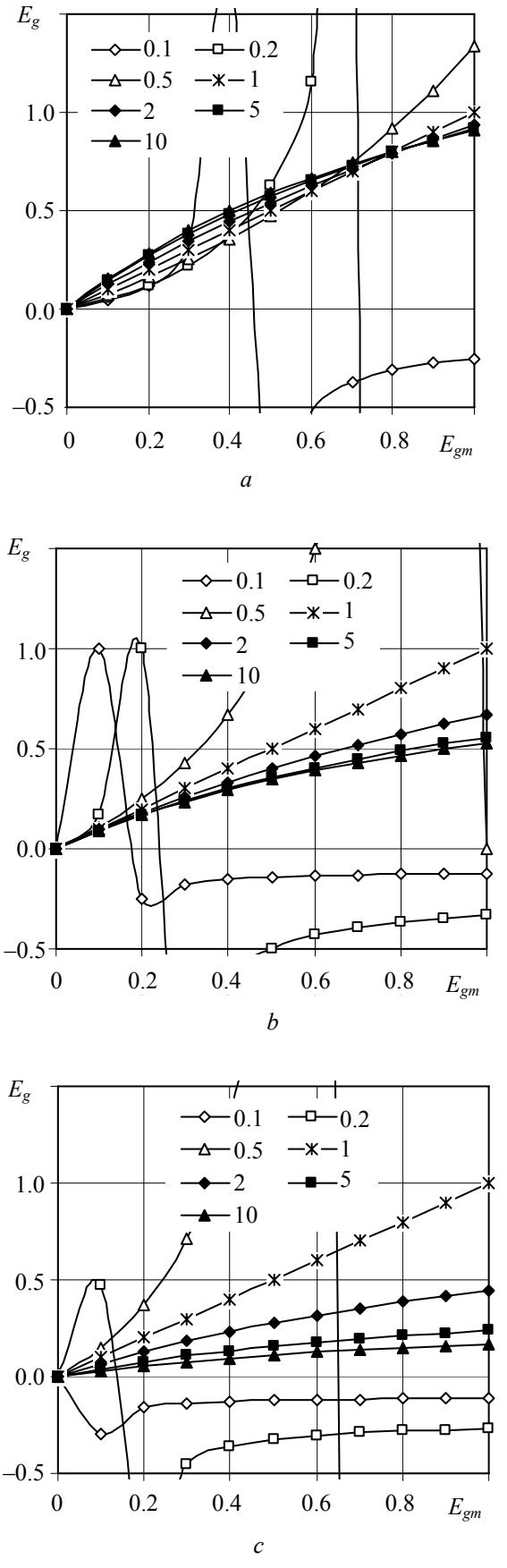

Fig. 2. Dependence of E_g on E_{gm} at direct flow and various m:
a – $L / V = 0.1$; *b* – $L / V = 1.0$; *c* – $L / V = 10$

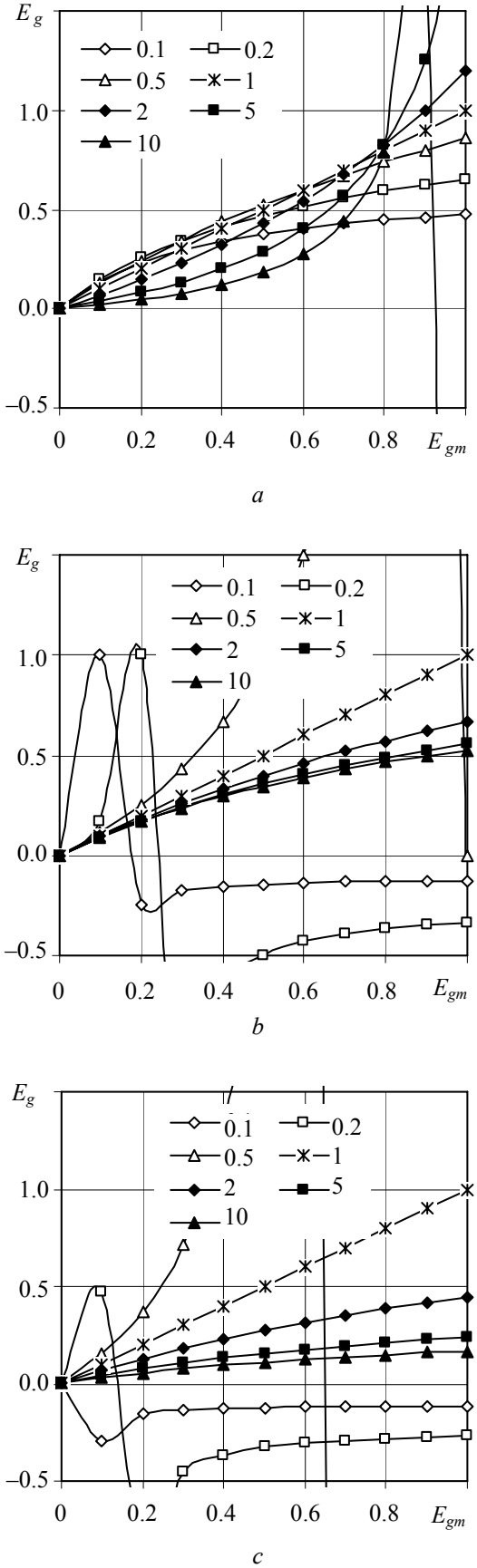

Fig. 3. Dependence of E_g on E_{gm} at countercurrent and various m: $a - L / V = 0.1$; $b - L / V = 1.0$; $c - L / V = 10$

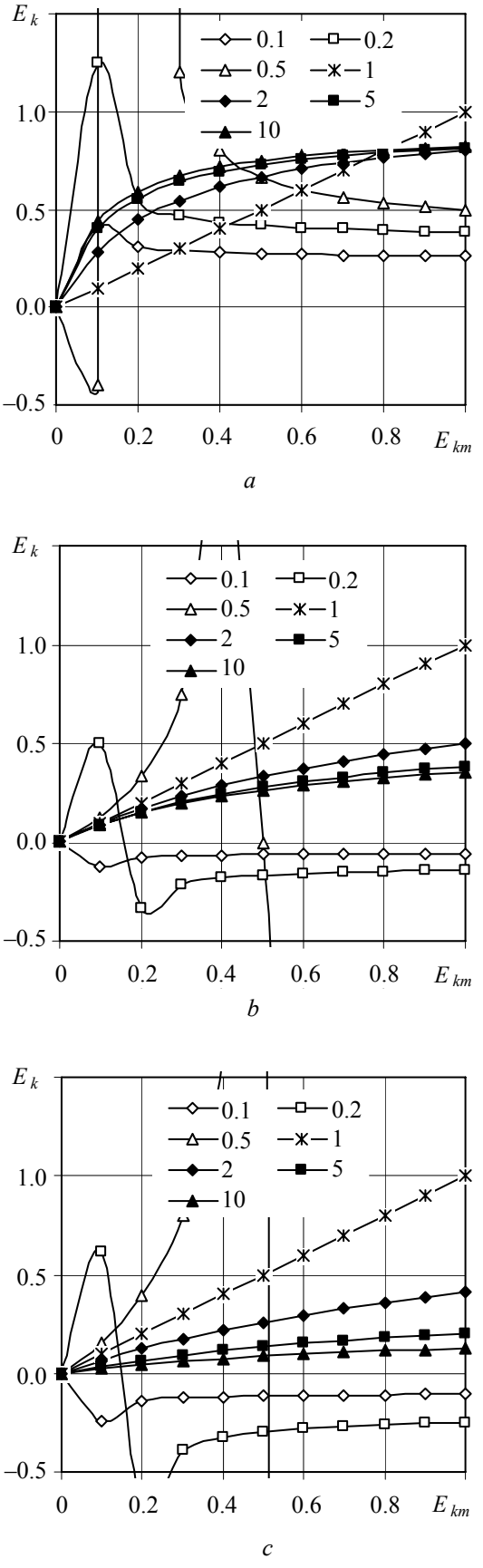

Fig. 4. Dependence of E_k on E_{km} at cross current and various m: $a - L / V = 0.1$; $b - L / V = 1.0$; $c - L / V = 10$

When the mixture on plates of a rectifying column is separated the concentration of vapor component changes. Thus on plates the change of values of distribution coefficient is possible. In that case it is enough to define the mass transfer efficiency only on one plate and to apply the calculated efficiency value on other plates with the identical design and work regime data of all plates. For this purpose it is possible to use the formula deduced from expression (3):

$$E = \frac{\frac{L}{mV} + C - h\frac{L}{mV} - h_1}{\frac{x_n - \frac{y_{n-1}}{m}}{x_n - x_{n-1}} + C - h\frac{L}{mV} - h_1} \qquad (6)$$

or its special case taking into account dependences (2):

$$E = \frac{\frac{L}{V} - 1 + C(m+1)}{mx_n - y_{n-1} + x_{n-1} - \frac{y_n}{m}}(x_n - x_{n-1}). \qquad (7)$$

Conclusion. The mass transfer efficiency rises with the increase in the distribution coefficient over unity for the considered direct-flow, counterflow and cross movement of the steam and liquid phases. For $m < 1$ the ratio of efficiencies depends on the form of flow organization and value m.

The received results can be used for the recalculation of mass transfer efficiency defined for a modeling mixture, for other mixtures which distribution coefficient exceeds unity.

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